Developing an engineering approach for migrating from prescriptive to performance-based specification for concrete

DEVELOPING AN ENGINEERING APPROACH FOR MIGRATING FROM PRESCRIPTIVE TO PERFORMANCE-BASED SPECIFICATION FOR CONCRETE

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Abstract

The integral variability of raw materials, lack of awareness and appreciation of the technologies for achieving quality control and lack of appreciation of the micro and macro environmental conditions that the structures will be subjected, makes modern day concreting a challenge. This also makes Designers and Engineers adhere more closely to prescriptive standards developed for relatively less aggressive environments. The data from exposure sites and real structures prove, categorically, that the prescriptive specifications are inadequate for chloride environments. In light of this shortcoming, a more pragmatic approach would be to adopt performance-based specifications which are familiar to industry in the form of specification for mechanical strength. A recently completed RILEM technical committee made significant advances in making such an approach feasible.

Furthering a performance-based specification requires establishment of reliable laboratory and on-site test methods, as well as easy to perform service-life models. This article highlights both laboratory and on-site test methods for chloride diffusivity/electrical resistivity and the relationship between these tests for a range of concretes. Further, a performance-based approach using an on-site diffusivity test is outlined that can provide an easier to apply/adopt practice for Engineers and asset managers for specifying/testing concrete structures.

1. Why there is a need to change the current practice and specification?

Chloride transport into concrete is controlled primarily by the availability of chloride ions on the surface and properties of cover concrete such as diffusivity, porosity and ionic concentration of pore fluid. There are several other factors that also contribute to the transport and subsequent corrosion of reinforcement including temperature, moisture gradient, chloride binding, pore refinement and critical chloride threshold.

In order to specify a concrete that will last the design life of, say, 120 years, it is necessary to understand the contributing factors and their interconnectivity. It is also known that effects such as shrinkage, structural loading and other deterioration mechanisms can increase the rate of chloride transport which may not be obvious from controlled laboratory testing on unloaded, small concrete specimens. Fig. 1 shows the chloride ingress data from two concrete structures exposed to marine environment. The mix design shows that both concretes conform to BS 8500 design requirements [1]. However, as the 7 year and 18 year data show, chlorides have reached the rebar location in sufficient quantity to initiate corrosion. It is interesting to note that Fig.1b refers to a concrete designed to a higher specification, with 460 kg/m^3 of CEM I, 0.4 water/binder (w/b) ratio, and a 28-day strength of 66 MPa. These are not isolated structures with high chloride ingress, but it is well known that the majority of the structures in XD and XS environments will not reach the 120 year design life without several significant interventions during their lifespan. In this context, one of the options for asset owners is to test concrete to determine its initial performance or invoke the option of Designed or Proprietary concretes outlined in BS 8500 [2]. For chloride ingress, there are several factors that control or govern performance, but as an interim method, determining/specifying diffusivity as well as capturing the mix details in sufficient depth for further analysis is a step in the right direction. In the next section, test methods commonly used in Europe to determine diffusivity are reviewed and the relationship between the methods is studied with a view to identify suitable methods for site and laboratory application.

2. Laboratory and onsite test methods for assessing chloride ingress

Chloride transport through a small section of concrete can be classified into three phases, non-steady (when the inward flow is not equal to outward flow – binding is effective), steady state (when inward and outward flow is equal) and attenuation state (when other ions take priority over chloride ions). Test methods mimic these phases in a small specimen and with an appropriate mathematical expression, it is possible to determine a diffusion coefficient when the test is concentration driven. Non-steady tests are more rapid and can replicate flow similar to the real structure, but decoupling the effect of binding is difficult, unless binding capacity is determined separately. Steady-state tests take longer to establish but it is perceived that they replicate the flow of free chloride ions and therefore can better assess the risk of reinforcement corrosion. An electrical field can be applied to accelerate the flow of chlorides in a test and therefore complete the test in short duration. These are classified as migration tests, and the resulting coefficient is either steady or non-steady state migration coefficient, similar to the phases in a diffusion test.

Results from different methods are presented below and the discussions will focus on the sensitivity of the coefficient to mix properties such as w/b ratio and type of binder and also on the standard error between the three replicate tests.

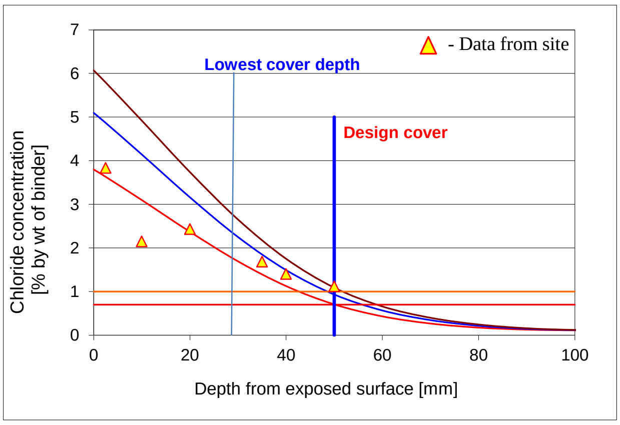


Fig. 1a, chloride profile from a concrete pier situated off the Atlantic coast (Cl^- concentration 15,700 ppm) after 7 years of exposure. Concrete mix information available are 0.46 w/b, 400 kg CEM I, C40/50 with a design cover of 50 mm and minimum cover on site of 27 mm.

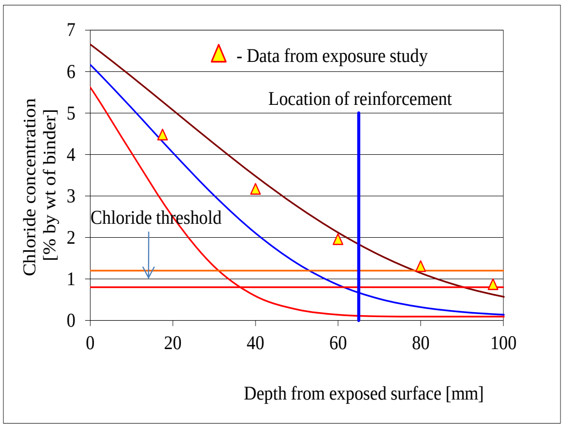


Fig. 1b, chloride profile from a concrete pier off North sea (Cl^- concentration 8,800 ppm) after 18 years of exposure. Concrete mix information available are 0.40 w/b, 460 kg CEM I, sample taken from XS2, compressive strength f_{28} = 66 MPa, design and actual cover is 65 mm.

Non-steady state measurement

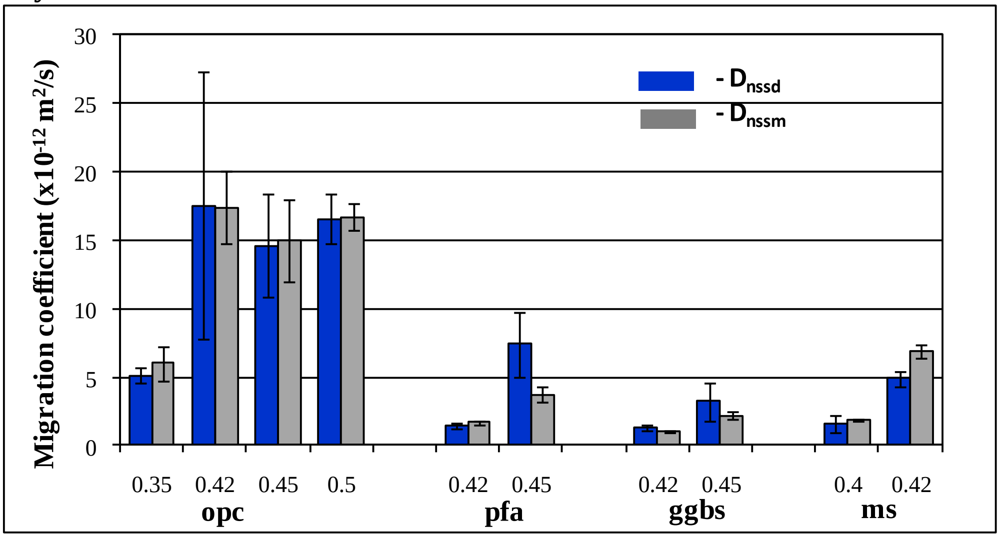


Fig. 2 Effect of mix properties on the non-steady state coefficient. D_{nssd} – Represent non-steady state diffusion coefficient as per NT Build 443, and D_{nssm} – represents non-steady state migration coefficient as per NT Build 492. Mix design and test details are given elsewhere [3].

Fig. 2 shows that both coefficients are sensitive to mix variables such as w/b and type of binder. For the exception of 0.42 w/b opc, which was found to have large cavities, all the other results are in line with previous published literature. In order to evaluate the effectiveness of other methods, the D_{nssd} was considered as reference value. This is mainly due to the fact that this test replicates the real-life scenario in which chloride ions move through concrete under a concentration gradient. However, this highlights the challenge in conducting the non-steady state test as it is lengthy and requires considerable effort/man power including chemical analysis. The advantage of the migration-based test over diffusion test is that it is more rapid (1-4days), chemical analysis is not required, utilizes considerably less man power, but requires chemicals and a dedicated test set-up as described in NT Build 492. The relationship between the two coefficients is known to be linear with a high coefficient of regression [4, 5]. In addition, a lower standard error for D_{nssm} as compared to D_{nssd} would provide more confidence in the migration test method. Since the completion of the study, this test was successfully utilized as a quality control test for a major construction work in Ireland. One of the major advantages is that both D_{nssd} and D_{nssm} are commonly used for service-life prediction with the help of Fick's law based models.

Bulk electrical resistivity

Bulk resistivity was measured on concrete specimens prepared for non-steady state migration test: 50 mm thick and 100 mm diameter concrete cylinders were vacuum saturated in $Ca(OH)_2$ solution.

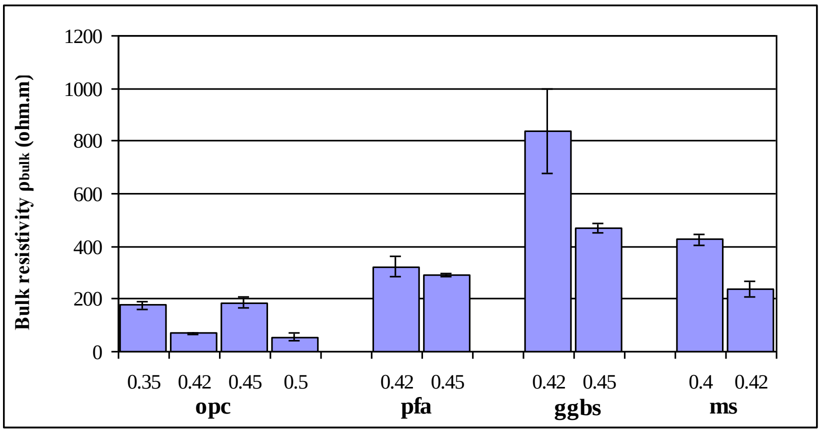


Fig. 3 Effect of mix properties on the bulk resistivity, ρ_{bulk}

Resistivity is a very rapid (5 mins) test and the results presented in Fig. 3 show a very high repeatability. Use of ionic saturated test specimens, lack of polarization due the use of AC voltage source, instantaneous measurement as compared to tests that run over days, all must have contributed to improving the repeatability. Moreover, published literature suggests that bulk resistivity of either water saturated or ionic saturated concrete specimens can be used to predict the steady or non-steady state migration coefficients [6-7]. This relationship is further explored by researchers for predicting the chloride transport as well as the onset and the propagation of reinforcement corrosion [8-9].

Steady state measurement

Similar to the coefficients discussed previously, steady-state migration coefficient, D_{ssm} in Fig. 4 shows that it is sensitive to mix variables and, generally, decreased with a decrease in w/b. The coefficients were significantly lower for concretes containing supplementary cementitious materials, with the exception of pfa concretes. The beneficial effect is more evident for concrete with higher w/b. A higher value for D_{ssm} for pfa concretes could be attributed to the low reactivity of the pfa blend used in this experimental programme. Tests undertaken after two years on samples matured in an ideal laboratory condition showed a substantial reduction in the coefficients. It is expected that for all concrete mixes, hydration process continues beyond 28 days and further hydration products that are formed within the available space including pore walls. This will refine the pore structure and make the concrete less permeable.

The steady-state migration test can be considered as more rapid than the non-steady state diffusion test, but it requires 3-7days to complete which makes it less rapid than non-steady state migration test and bulk electrical resistivity test. Test requires a dedicated experimental set-up and set of skills for determining the coefficients.

$D_{in\ situ}$ refers to in situ migration coefficient determined using a surface based chloride migration test (Permit Ion Migration Test) and the figure 4 clearly shows that $D_{in\ situ}$ is sensitive to both w/b and type of binder. This figure also shows that the error associated with $D_{in\ situ}$ is low (similar to D_{ssm}). The data obtained from test carried out after 2 years reveal that the coefficient has halved in most cases. This confirms that the test is also sensitive to the maturity of the concrete. The advantage of the Permit is that as it is a surface-based test, it requires no coring and therefore no physical damage to concrete structure, it can test concrete in-situ. The coefficient will reflect, therefore, the interaction of structural loading, shrinkage, thermal strains, damage/pore blocking due to carbonation or damage due to other durability mechanisms, leaching, etc.

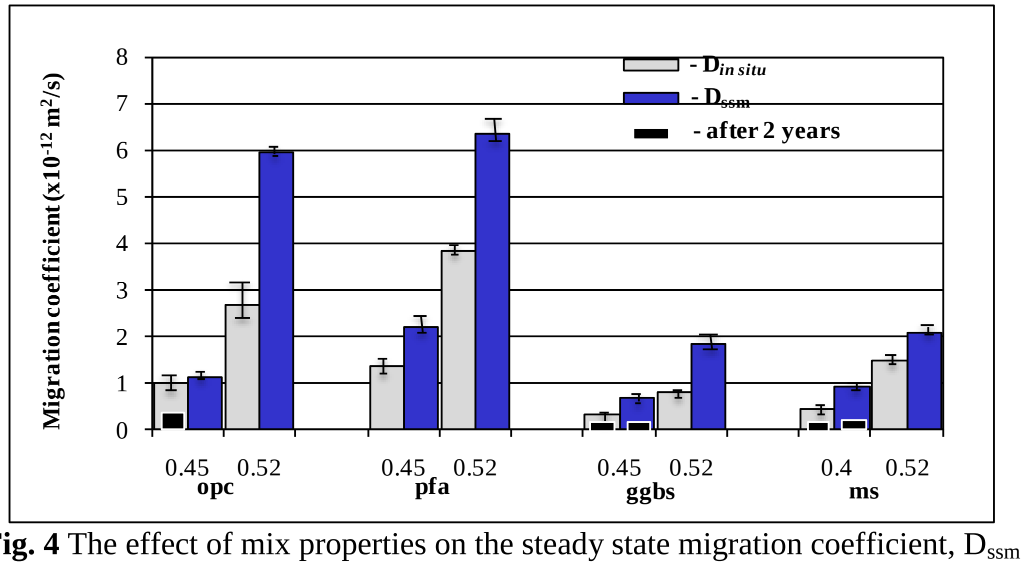


Fig. 4 The effect of mix properties on the steady state migration coefficient, D_{ssm}
Note: test voltage 12-60 v, 0.55 M NaCl solution, for further details refer to [3]

Relationship between the coefficients

The relationship between the various test results are discussed in the following section with a focus on the relationships between the coefficients and existing service life prediction models and also to identify further details regarding chloride ingress into concrete viz. chloride binding, volumetric porosity, etc.

It is worth noting that the discussion is limited to the concrete studied, mainly, 0.45-0.52 w/b, a higher w/b may warrant a higher slope ≥ 0.3, as reported elsewhere [7].

Nilsson et al (1996) suggested a relationship between steady and non-steady coefficient, and the mathematical expression is given in Eq. 1

$$D_{nssd} = \frac{D_{ssd}}{\varepsilon\left(1+\frac{\partial C_b}{\partial C_f}\right)} \qquad \text{Eq. 1}$$

ε - porosity, and $\frac{\partial C_b}{\partial C_f}$ – represents binding capacity

The data presented in Fig. 5 show that this relationship can be proven experimentally. Therefore, the slope of the line, 4.42, represents the combined effect of binding and porosity on chloride transport. Therefore, in modelling the chloride transport, knowledge of three of these parameters will be invaluable. Porosity and diffusivity can be determined relatively easily, binding capacity may be estimated from the literature for the binder type and quantity, and this will make service life modelling easier to perform. Note that the slope of the line may change due to the experimental set-up; for Example, if 1.0 M NaCl solution is used instead of 0.55 M used in this study, then the slope decreases.

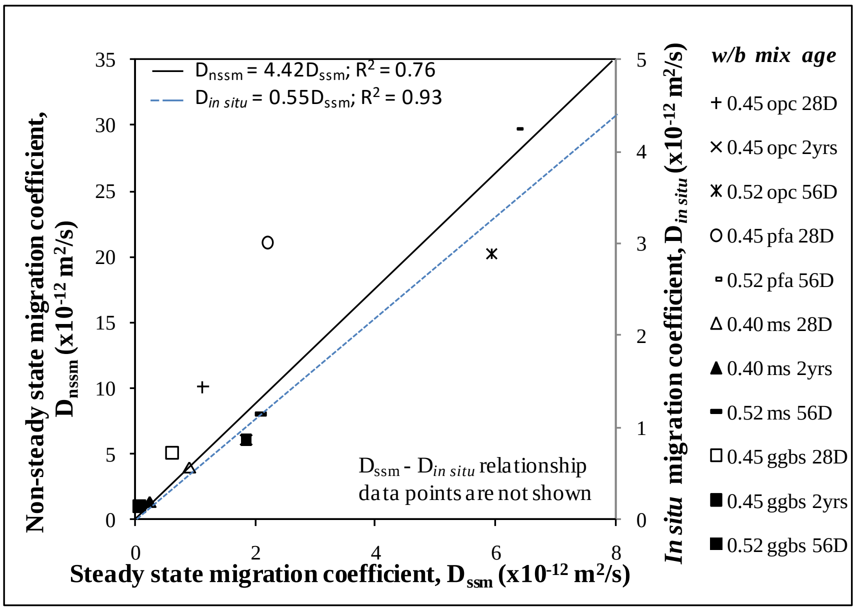


Fig. 5 Relationship between different migration coefficients [3].

Also presented in Fig. 5 is the relationship between coefficients evaluated from Permit and a conventional steady-state migration test (D_{ssm}). If both tests use the same principle, the coefficients should be linearly related and equal in magnitude; however, the slope is 0.55 and not unity. This is attributed to the difference in test set-up. The conventional steady state test uses 1.2 L of 0.55 M NaCl solution whereas PERMIT uses 0.45 L of 0.55 M NaCl. The Permit will electrically charge a region for accelerating the chloride flow. As the effective zone of influence of the electrical filed depends on the quality of concrete, cracking and contamination, this cannot be equated directly to a laboratory based test set-up which assumes a linear voltage drop per meter of specimen. These differences could influence the relationship and can be considered the reason as to why $D_{in\ situ}$ is lower than D_{ssm}. Nevertheless, the coefficients are linearly related and therefore one can represent the other within the range of concrete studied.

Electrical resistivity, whether bulk or surface based, can be related to diffusion/migration coefficient and is reasonably well established [3-9]. The mathematical expression between surface resistivity, determined using the Wenner four probe technique, and $D_{in\ situ}$ is [3]:

$$D_{in\,situ}\ (x10^{-12}) = \frac{140}{\rho_{Wenner}} \qquad \text{Eq. 2}$$

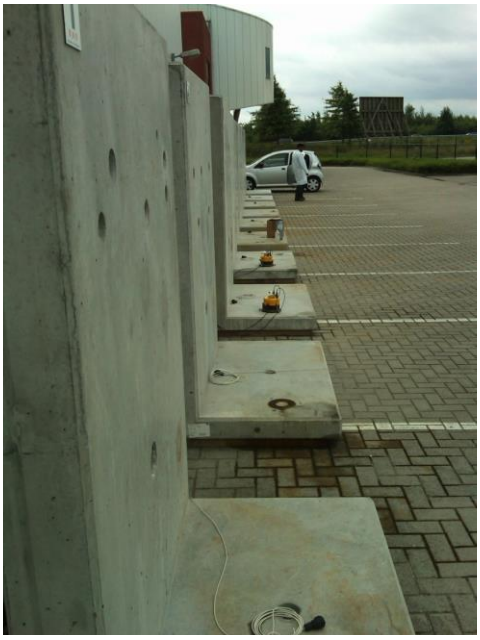
Where, ρ_{Wenner} represents the surface resistivity in Ω-m. The coefficient of regression for the relationship is 0.72.

The benefit of using a relationship such as Eq. 2, is that assessing a large structure becomes easier. Resistivity measurements and mapping can be easily performed. This allows identification of areas of relative weakness/strength for further analysis. Once such a mapping has been produced, Engineers can decide to further investigate weak areas by gathering concrete dust-drillings for chloride analysis and Permit testing. Diffusivity from Permit or similar test can be used for chloride modelling and relationships, as in Eq. 2 will allow extension in prediction to all areas of the structure. Further, by superimposing the above information on cover meter data will assist engineers in the decision regarding the remaining life of a structure across the various locations. It is important to note that resistivity data will be influenced by moisture distribution, presence of chloride ions or carbonation and surface emanating cracks. Therefore the resistivity mapping alone should not be used in decision making, but further analysis as suggested before should be performed. The mapping, however, can be used as a progressive asset management tool for critical structures (or sections), where regular monitoring is a necessity.

3. Developing an approach for performance testing and modelling – Venlo RRT programme

The recently completed RILEM PSC technical committee held a round-robin test program (RRT) to establish the validity of site-based methods and the performance-based approach they can offer for testing/specification. Eight concrete mixes were considered, and the mix details are shown below in Fig. 6. Further details are available in the state-of-the-art report [11].

The Permit test was performed to determine $D_{in\ situ}$ for all the eight mixes. The concrete samples were just over two weeks old at the time of testing, so concrete maturity was determined using resistivity data, so that $D_{in\ situ}$ at 180 days could be determined. This approach was validated by repeating the test at a later age (refer to [11]). Using $D_{in\ situ}$ at 180 days, chloride transport modelling was performed using ClinConc [12]. The time for the chloride concentration to reach an assumed chloride threshold of 0.1% by mass of concrete was considered as the end of service life (time for corrosion initiation). Although such an approach ignores the corrosion propagation time, it should be considered as a conservative and safe option for designing concrete structures. Safety refers to the reliability/repeatability of the testing and prediction methods for quantifying chloride transport. Users can add the propagation time, if available for their structures to get a more realistic service life.



Sample	w/b	CEM	Date	Age at testing (days)	Measured $D_{in\ situ}$ (10^{-12} m^2/s)
1	0.44	I	15-Apr-12	18	0.62
2	0.44	I		18	0.14
3	0.54	I		17	0.85
4	0.54	I		17	1.85
5	0.40	II B/V		16	0.95
6	0.40	II B/V		16	1.05
7	0.59	II B/V		14	2.64
8	0.59	II B/V		14	1.89

Fig. 6 Concrete panels used in Venlo RRT programme and the mix design and test details.

Table 1 Summary of the predicted performance of Samples 1-8 in XS3 exposure environment for C_s = 14 g/L

Sample	Predicted D value at 180 days ($D_{in\ situ}$ x $10^{-12}m^2/s$)	Actual Cover (mm)	Predicted Corrosion Initiation Time	Acceptable for XS3 exposure for 100 years of service Life	Suggested Improvement for 100 year Service Life
1	0.44	30	<10 years	No	Proper curing, increase binder content and cover ≥ 80mm
2	0.10	30	~ 50 years	No	Increase cover to 40mm
3	0.34	30	~ 10 years	No	Increase cover to 80mm
4	0.75	30	<10 years	No	Not suitable
5	0.25	30	~ 20 years	No	Increase cover to 70mm
6	0.27	30	~ 15 years	No	Proper curing, increase binder content and cover ≥ 70mm
7	0.51	30	≤ 10 years	No	Not suitable >> 80mm cover
8	0.37	30	~ 10 years	No	Increase cover to 80mm

Note: Covers higher than 70mm, are not viable for structural concretes due to lack of shrinkage control, so alternative mix design or surface treatment/cladding should be sought in such cases.

For the purpose of RRT, it was assumed that specimens are exposed to XS3 environments (i.e., salt concentration of 14 g/L) and for a cover of 30 mm, the time for initiation of corrosion (service life) was determined, refer to Table 1. The table also provides suggestions for improving the service life either by increasing the cover or by better curing the specimens.

The procedure outlined in Fig. 7 shows how a performance-based specification can be developed using $D_{in\ situ}$ for a range of concrete specimens. As $D_{in\ situ}$ is a steady state coefficient, the critical value of 0.35x 10^{-12} m^2/s can be adopted irrespective of the binder type (binding capacity). Binding capacity can be considered at the modelling stage and as shown before this can be either estimated from the binder type/quantity or experimentally determined. This makes testing much easier and less complicated for industrial adaptation.

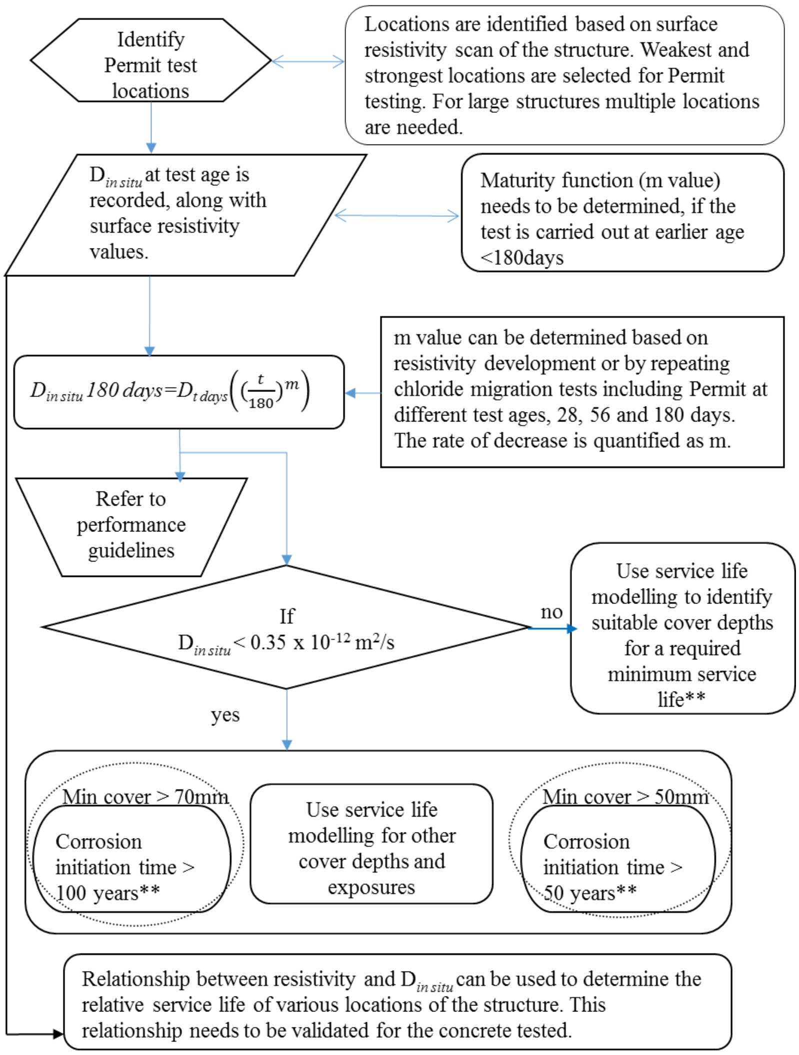


Fig. 7 Flowchart detailing the procedures involved in specifying concrete performance using $D_{in\ situ}$ for XS3 or XD3 exposure environments.

Moreover test can be repeated as and when required to confirm the quality (or quantify deterioration), estimate the remaining service life and decide on early remedial actions if necessary. Relationships presented in section 2 can be utilized as discussed before for estimating the remaining service life using a combination of surface resistivity and $D_{in\ situ}$. Such an approach is ideal for asset management where regular detailed inspection is a necessity.

4. Concluding remarks

This article reviewed the performance of two concrete structures in marine environments and shows the need for a performance-based approach for concrete specification. A review of the different test methods that can be successfully employed as quality control measures was carried out and the interrelationship between these tests also provided. The discussions in this paper gave emphasis to site based tests. Further, a methodology for developing performance-based specification was outlined using Permit (a site based chloride diffusivity test) and chloride ingress modelling. The advantages of this approach include, and are not limited to, (1) determination of diffusivity in a larger undisturbed specimen, on site, with all the stresses / stain of a real structure and (2) providing a means to benchmark the performance measure at an early age, so that any further deterioration can be quantified easily and timely interventions carried out.

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